Short Block-length Codes for Ultra-Reliable Low Latency Communications

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***Abstract*—Ultra-reliable low latency communication (URLLC) has emerged as one of the most challenging features of 5G and beyond communication systems due to its stringent requirements for reliability and latency. This paper provides a comprehensive review and analysis of short block-length codes for URLLC applications, focusing on their performance, complexity, and suitability for various use cases. We analyze various candidate channel coding techniques including BCH codes, tail-biting convolutional codes (TB-CC), turbo codes, LDPC codes, and polar codes. Our comparison encompasses key metrics such as block error rate (BLER) performance, proximity to normal approximation benchmarks, and computational complexity. The results indicate that extended BCH codes with order statistics decoding (OSD) offer the best performance approaching the normal approximation benchmark, while polar codes with successive cancellation list (SCL) decoding provide a favorable performance-complexity tradeoff. Finally, we identify several promising research directions to further improve the performance of URLLC channel codes, including the development of low-complexity ML-like decoders, self-adaptive coding schemes, and space-frequency channel coding approaches.**

***Index Terms*—ultra-reliable low latency communications, short block-length codes, 5G, channel coding, normal approximation, BCH codes, polar codes, TB-CC**

I. Introduction

The fifth generation (5G) of mobile networks has introduced three primary service categories: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communications (URLLC) [1]. Among these, URLLC represents one of the most challenging aspects due to its conflicting requirements of ultra-high reliability and ultra-low latency.

URLLC applications span a wide range of use cases with varying requirements. Factory automation and tele-surgery demand the strictest reliability level of $(1-10^{-9})$ with end-to-end latency below 1ms. Other applications such as smart grids, tactile internet, and intelligent transportation systems have somewhat relaxed reliability requirements of $(1-10^{-3})$ to $(1-10^{-6})$ with latencies between 1-100ms [2]. The 5G standard targets a reliability of $(1-10^{-5})$ with a user plane latency of 1ms for URLLC applications [3]. However, certain industrial and medical applications requiring even stricter performance (¡0.1ms latency with 10^{-9} BLER) may need specialized solutions beyond what 5G can offer.

The physical layer design for URLLC faces significant challenges. Using short packets reduces latency but sacrifices coding gain, while employing stronger error correction codes improves reliability but increases processing delays. This presents a complex tradeoff that must be carefully balanced to meet URLLC requirements. The 3GPP has specified that channel coding for URLLC requires further investigation, particularly for information blocks of less than 1000 bits [4].

In this paper, we present a comprehensive analysis of various channel coding techniques for URLLC, focusing on their suitability for short block lengths. We evaluate their performance in terms of reliability, rate efficiency, and computational complexity. Furthermore, we identify key research directions that could lead to substantial improvements in URLLC channel coding performance.

II. Key Metrics, Requirements, and Performance Benchmarks

A. Latency

In the physical layer, user plane latency is the primary concern, defined as the time required to successfully deliver a data block from transmitter to receiver via the radio interface. This latency comprises four main components:

- Time-to-transmit latency: Should be in the order of hundreds of microseconds
- Propagation delay: Dependent on the distance between transmitter and receiver
- Processing latency: Including channel estimation, encoding/decoding times
- Retransmission time: Should be minimized or eliminated if possible

B. Reliability

Reliability is defined as the success probability of transmitting K information bits within the specified user plane latency at a certain channel quality. Sources of failure include packet loss, late arrival, or residual errors. Throughout this paper, we use Block Error Rate (BLER) as the primary metric for comparing the reliability performance of different coding schemes.

C. Flexibility

The flexibility of a channel coding scheme is another crucial aspect. Bit-level granularity of codeword size and operating rate is desirable for URLLC applications [3]. The coding scheme should not restrict the actual coding rate used in transmission and should enable Hybrid Automatic Repeat Request (HARQ) functionality, although the number of retransmissions should be kept minimal to reduce latency.

D. Performance Benchmark

Two important effects need to be considered when evaluating short block length codes. First, reducing the block length inherently increases the gap to Shannon's limit due to fewer channel observations. Second, many modern codes (e.g., LDPC, Turbo) exhibit increased gaps to finite length bounds with shorter blocks, often due to suboptimal decoding algorithms.

For our performance benchmark, we use the normal approximation (NA) [5], which incorporates the effects of finite block length:

$$R = C - \sqrt{\frac{V}{N}}Q^{-1}(\epsilon) + \frac{1}{2N}\log_2(N) \tag{1}$$

where R is the code rate, C is the channel capacity, V is the channel dispersion, ϵ is the average BLER, N is the code block length, and $Q(.)$ is the cumulative distribution function of the standard normal distribution.

III. Candidate Short Block-length Channel Codes

A. BCH Codes

Bose, Chaudhuri, and Hocquenghem (BCH) codes are powerful cyclic error-correcting codes characterized by a guaranteed error-correction capability t. The minimum distance d_{min} of BCH codes is at least $2t+1$ [6]. While traditionally decoded using bounded-distance decoders like the Berlekamp-Massey algorithm, near-ML performance can be achieved using the Order Statistics Decoder (OSD).

OSD is a soft-decision decoding algorithm that approaches ML performance through systematic reordering of the received bits by reliability and testing various error patterns. Recent advances in OSD design have significantly reduced the decoding complexity [7], making it viable for short block-length codes despite its computational demands.

BCH codes offer large minimum distances that prevent error floors at low BLERs. However, they lack flexibility as the block length and information length cannot be arbitrarily selected.

B. Convolutional Codes

Convolutional codes (CC) employ encoders with memory, with their error-correction capability increasing with memory order m. For short packet transmission, tail-biting convolutional codes (TB-CCs) are particularly relevant as they eliminate the rate loss associated with zero-tail termination [8].

The decoding complexity of convolutional codes scales exponentially with memory order for both Viterbi and BCJR algorithms [6]. TB-CCs were used in LTE for broadcast channels and control information and are currently considered for URLLC in 5G standardization.

C. Turbo Codes

Turbo codes combine parallel concatenation of convolutional encoders with iterative MAP decoding [6]. While highly effective for large block lengths, turbo codes with iterative decoding show performance gaps exceeding 1 dB from the finite-length benchmark for short and moderate block lengths.

LTE turbo codes perform well for medium block lengths and rates $\geq 1/3$ but degrade at lower rates and shorter blocks. Turbo codes offer 1-bit granularity for all coding rates and block sizes and support both chase combining and incremental redundancy HARQ [9].

D. LDPC Codes

Low-density parity-check (LDPC) codes with belief propagation (BP) decoding approach Shannon's limit for large block lengths. However, binary LDPC codes with iterative BP decoding perform poorly at short-to-moderate block lengths due to short cycles in the code's bipartite graph.

Protograph-based LDPC codes show improved performance for shorter blocks but still cannot match BCH or large-memory TB-CCs. LDPC codes excel in parallelizing the decoding algorithm. For 5G eMBB, two base graphs have been adopted: BG 1 for high data rates and long blocks, and BG 2 for low code rates and short blocks. Recent investigations have revealed error floors for LDPC codes at certain rates and block lengths [9].

E. Polar Codes

Polar codes leverage channel polarization to provably achieve capacity for binary-input discrete memoryless channels as code length tends to infinity [10]. The basic successive cancellation (SC) decoder has complexity $O(N \log N)$, but its recursive nature may introduce significant latency.

Successive cancellation list (SCL) decoding substantially improves performance by keeping multiple decoding paths. CRC-aided SCL (CA-SCL) further enhances performance by using CRC checksums to select the correct path from the list [11].

Polar codes have been selected for short block control channels in 5G eMBB and have demonstrated superior performance over LDPC codes for short blocks and low rates without error floors [9]. They offer 1-bit granularity across all coding rates and block sizes, though implementation complexity increases with list size.

IV. Performance Comparison

A. Reliability Performance

Fig. 1 illustrates the BLER versus SNR performance for various channel codes with rate $R = 1/2$ and block length $N = 128$ under maximum likelihood decoding (MLD) over a binary-input additive white Gaussian noise (BI-AWGN) channel.

Key observations from the reliability comparison:

- Extended BCH codes approach the normal approximation benchmark with only a 0.1dB gap at BLER=10^{-7}.

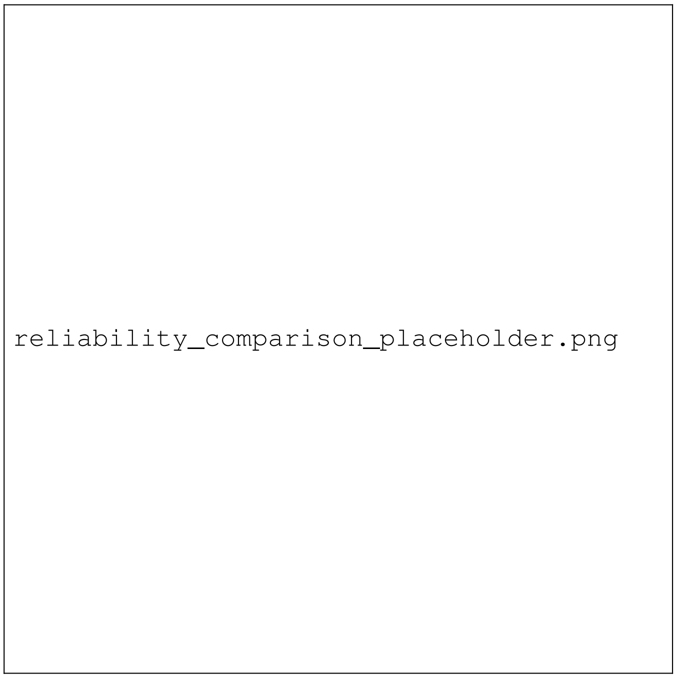

Fig. 1. Comparison of error performance for different rate $R = 1/2$ channel codes with codeword length $N = 128$ under MLD. The data for this figure comes from [2].

Fig. 2. Comparison of different channel codes with codeword length $N = 128$ with different rates at BLER=10^{-4}. The data for this figure comes from [2].

- TB-CC with memory $m = 14$ achieves a 0.1dB gap to the NA at BLER=10^{-5}, which increases to 0.3dB at BLER=10^{-7}.
- LDPC codes over large Galois fields (e.g., F_{256}) demonstrate performance similar to high-memory TB-CCs.
- The overall performance ordering is: eBCH ¿ TB-CC ¿ LDPC (F_{256}) ¿ Polar+CRC ¿ LDPC (binary) ¿ Turbo.

B. Rate Performance

Fig. 2 presents the rate performance of different channel codes at BLER=10^{-4} with codeword length $N = 128$.

Key observations:

- BCH codes with OSD (order 5) perform closest to the normal approximation across all SNRs.
- Polar codes with CA-SCL using list size $L = 32$ significantly outperform those with $L = 4$, at the cost of increased complexity.
- eMBB LDPC codes with BP decoding offer slightly better performance than CA-Polar with $L = 4$ while maintaining lower complexity.
- The gap to capacity increases at higher rates for all codes.

C. Complexity vs. Performance Trade-off

Fig. 3 illustrates the algorithmic complexity versus performance trade-off for various channel codes.

Key observations from the complexity-performance analysis:

- TB-CC with $m = 14$ offers excellent performance (0.3dB gap to NA) but exhibits prohibitive complexity ($\sim 10^7$ operations/bit).
- Extended BCH with OSD-5 provides the best performance (0.1dB gap to NA) at high complexity ($\sim 10^5$ operations/bit).
- Polar codes with SCL ($L = 32$) achieve good performance (0.5dB gap to NA) with moderate complexity ($\sim 10^3$ operations/bit).
- LDPC codes with BP decoding offer reasonable performance (0.8dB gap to NA) with low complexity ($\sim 10^3$ operations/bit).

The results indicate that polar codes provide the best balance between performance and complexity for URLLC applications.

V. Research Directions and Recommendations

Based on our analysis, we identify three primary research directions to further improve URLLC channel coding:

A. Low Complexity ML-like Decoders

While BCH codes with OSD offer superior performance, their decoding complexity remains a challenge. Recent work [7] has demonstrated significant complexity reduction while maintaining performance. Developing enhanced OSD algorithms with bounded complexity or segmented and sufficiently conditioned OSD approaches could help establish a fundamental balance between performance and complexity.

B. Self-Adaptive Coding Schemes

Current rate-adaptive schemes suffer from channel estimation overhead (5-8ms in LTE) and dependence on retransmissions. Self-adaptive channel coding [12] could eliminate the

Fig. 3. Algorithmic complexity versus performance for different rate-1/2 channel codes with block length $N = 128$ at BLER=10^{-4}. The data for this figure comes from [2].

need for CQI feedback by automatically adapting to channel conditions. Key research areas include:

- Joint design of coding and modulation schemes
- Reducing pilot sequence length for channel estimation
- Near-ML decoding without requiring accurate CSI at the receiver

C. Space-Frequency Channel Coding

In contrast to current cellular systems that prioritize spatial multiplexing for throughput, URLLC applications could benefit from spatial diversity to increase reliability. Research opportunities include:

- Using transmit and receive antennas for spatial diversity rather than multiplexing
- Reducing OFDM symbols per resource block to decrease latency
- Developing a unified framework for space-frequency channel codes that provide varying reliability levels for low-latency communications

VI. Conclusion

This paper has presented a comprehensive analysis of short block-length channel codes for ultra-reliable low latency communications. Our findings indicate that:

- BCH codes with OSD provide the highest reliability due to their large minimum distances but at high computational complexity.
- TB-CCs with large memory offer excellent performance but prohibitive complexity.
- Polar codes with SCL decoding achieve reliability of $(1 - 10^{-4})$ with only 0.5dB gap to the normal approximation at reasonable complexity, representing the best performance-complexity trade-off.
- LDPC codes with BP decoding offer good performance with low complexity but show error floors at certain rates and block lengths.

To meet the extreme requirements of URLLC applications, especially those beyond 5G capabilities, significant advancements are needed in low-complexity ML-like decoders, self-adaptive coding schemes, and space-frequency channel coding approaches. These developments will be crucial for enabling mission-critical applications such as tele-surgery, factory automation, and power electronics industrial control that demand sub-millisecond latencies with ultra-high reliability.

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